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Three new X-ray pulsars detected in the Small Magellanic Cloud and the positions of two other known pulsars determined.

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ABSTRACT

Three new X-ray pulsars have been detected in the Small Magellanic Cloud (SMC) and the positions of two others have been determined, with archive Chandra data. A series of five observations of the SMC took place between May and October 2002. Analysis of these data has revealed three previously unknown X-ray pulsars at pulse periods of 34, 503 and 138 seconds. The position of pulsar XTE J0052-725, which was originally detected by RXTE on June 19 2002, was also accurately determined and a previously detected 7.78s RXTE pulsar was identified as the source SMC X-3.

Key words: Be stars - X-rays: binaries: Magellanic Clouds.

1 INTRODUCTION

The Magellanic Clouds are a pair of satellite galaxies which are gravitationally bound to our own but which have structural and chemical characteristics differing significantly from each other, and from the Milky Way. These differences are likely to be reflected in the properties of different stellar populations. The Small Magellanic cloud (SMC) is located at a distance of about 60 kpc (Harries, Hilditch, & Howarth, 2003) and centred on a position of R.A. 1hr Dec. -73^o. It is therefore close enough to be observed with modest ground based telescopes whilst at the same time providing an opportunity to study and compare the evolution of other galaxies.

Intensive X-ray satellite observations have revealed that the SMC contains an unexpectedly large number of High Mass X-ray Binaries (HMXB). At the time of writing, 46 known or probable sources of this type have been identified in the SMC and they continue to be discovered at a rate of about 1-3 per year, although only a small fraction of these are active at any one time because of their transient nature. All X-ray binaries so far discovered in the SMC are HMXBs (Coe 2000).

Most High Mass X-ray Binaries (HMXBs) belong to the Be class, in which a neutron star orbits an OB star surrounded by a circumstellar disk of variable size and density. The optical companion stars are early-type O-B class stars of luminosity class III-V, typically of 10 to 20 solar masses that at some time have shown emission in the Balmer series lines. The systems as a whole exhibit significant excess flux at long (IR and radio) wavelengths, referred to as the infrared excess. These characteristic signatures as well as strong Hα line emission are attributed to the presence of circumstellar material in a disk-like configuration (Coe 2000, Okazaki and Negueruela 2001).

The mechanisms which give rise to the disk are not well understood, although fast rotation is likely to be an important factor, and it is possible that non-radial pulsation and magnetic loops may also play a part. Short-term periodic variability is observed in the earlier type Be stars.The disk is thought to consist of relatively cool material, which interacts periodically with a compact object in an eccentric orbit, leading to regular X-ray outbursts. It is also possible that the Be star undergoes a sudden ejection of matter (Negueruela 1998, Porter & Rivinius, 2003).

Be/X-ray binaries can present differing states of X-ray activity varying from persistent low or non-detectable luminosities to short outbursts. Systems with wide orbits will tend to accrete from less dense regions of the disk and hence show relatively small outbursts. These are referred to as Type I and usually coincide with the periastron of the neutron star. Systems with smaller orbits are more likely to accrete from dense regions over a range of orbital phases

and give rise to very high luminosity outbursts, although these may be modulated by the presence of a density wave in the disk. Prolonged major outbursts, which do not exhibit signs of orbital modulation, are normally called Type II (Negueruela 1998).

2 THE CHANDRA DATA

A Chandra survey of the SMC bar region, initiated by Zezas et al., covered five separate fields between May and October 2002 (Zezas et al., 2003). The positions covered by the ACIS-I arrays from these observations are shown in relation to known pulsars in Figure 1. These have been overlaid on a neutral hydrogen density image of the SMC (Stanimirović et al. 1999).

The standard ACIS-I0123S23 CCD configuration was used although all sources discussed in this paper were found in the ACIS-I region which provides a $16.9' \times 16.9'$ field of view. Exposure times were between 7.6 and 11.6 ksec. Data were extracted from the ACIS level 2 event fits files which were taken with a frame readout time of 3.241 s. Using the CIAO v3 software, these observations were barycentrically corrected after which potential sources were detected using the *wavdetect* algorithm. Background was subtracted using rectangular regions of varying sizes, after which timing analysis of the lightcurves was carried out using both Lomb-Scargle and Fourier Transform algorithms. The Starlink PERIOD programme was used to generate pulse profiles folded on the resultant periods and these were then fitted with a sine function from which the pulsed fractions were determined.

Three of these observations (2946, 2947 and 2948) yielded significant results in the detection and identification of X-ray pulsars. These are summarised in Table 1 which also includes two previously known sources seen in the same data. The positional errors generated by *wavdetect* have been combined in quadrature with the Chandra nominal 90% confidence radial uncertainty of 0.6 arcsec to give the errors shown.

Spectral information for these sources was obtained using the CIAO *psextract* tool. The spectra were initially binned to a minimum of 10 counts per bin using the FTOOLS utility GRPPHA before being analysed with XSPEC. It was found however, that in the case of the three weakest sources this resulted in a poor fit and these were therefore binned to 2 counts per bin. Channel energy outside the limits of 0.3 keV and 10 keV was ignored. The spectra were then fitted to an absorbed powerlaw model, the results of which are summarised in Table 2. χ^2_v for the weaker sources would not be statistically valid, because of the relatively low number of counts, and has been omitted. The spectra are shown in Figure 4.

3 INDIVIDUAL SOURCES

3.1 XTE J0052-725

Pulsar XTE J0052-725 was originally detected by RXTE on June 19 and 26, 2002 (Corbet et al., 2002). The Chandra data show an X-ray source in Observation ID 2946 which took place on 4 July 2002 (MJD 52459) between 06:47:00 and 10:37:01 hrs. Timing analysis revealed a period of $82.46 \pm 0.18s$ at a confidence level of $> 99\%$. This period is within 0.06s of the one detected by RXTE and the position lies 6 arc minutes from the original mean RXTE location. It is therefore concluded that these are the same pulsar. The Chandra power spectrum is shown in Figure 2.

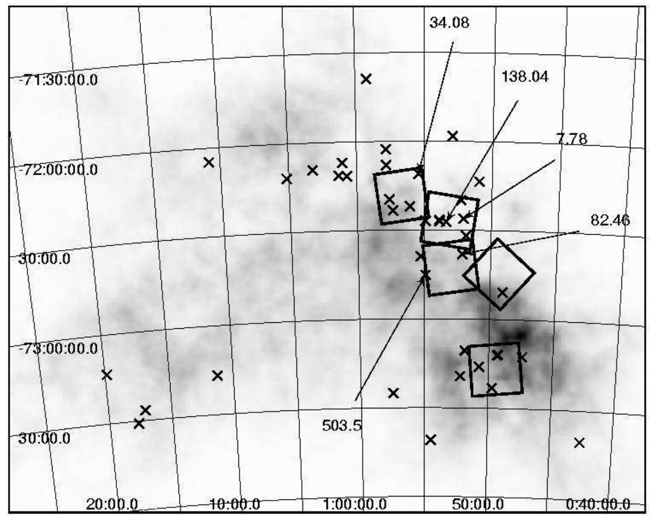

Figure 1. Positions covered by the ACIS-I arrays from Chandra observations 2944 - 2948, overlaid on a neutral hydrogen density image of the SMC. The newly identified pulsars are indicated by their pulse period, those already known are shown with a cross.

This source registered a total of 5255 counts and was therefore bright enough to test the pulse profiles for energy dependance. Folded profiles for the 0.3-2.5 keV and 2.5-10 keV energy bands are shown in Figure 3. The lower energy band contained about 60% of the photons but had a pulsed fraction of only 28% ± 2% as compared to 42% ± 3% in the higher energy 40%. The spectrum, fitted to an absorbed powerlaw model, is in Figure 4. Assuming a distance of 60 kpc to the SMC, the luminosity was 34.2×10^{35} ergs s^{-1}. The relatively high value of N_H at 0.69×10^{22} cm^{-2} may imply that this source is at a greater depth into the SMC, and hence at a greater distance, or may simply reflect a greater neutral hydrogen density in that region. This source has been identified with the optical counterpart MACS J0052-726#004 (Tucholke, de Boer, & Seitter, 1996).

3.2 SMC X-3

SMC X-3, which was first detected in 1978(Clark et al. 1978), has now been identified from the Chandra data with a previously detected 7.78s RXTE pulsar. Observation ID 2947, which took place on 20 July 2002 (MJD 52475) between 23:03:50 and 01:46:41 hrs, shows an X-ray source consistent with the position of the optical counterpart proposed for SMC-X-3 by Crampton et al., 1978. Timing analysis shows the Chandra object to have a pulse period of $7.781 \pm 0.002s$ with a confidence of $> 98\%$. An X-ray pulsar with a pulse period of $7.781 \pm 0.002s$ was detected by RXTE in early 2002 and on eight subsequent occasions, giving a probable binary period of 45.1 ± 0.4 days (Corbet et al., 2003). The position of the RXTE source was tentatively

Obj.	Name	R.A. *(J2000)*	Dec.	error *(arcsecs)*	P_{pulse} *(s)*	Counts	Pulsed fract (%)	ObsID	Date
1	XTE J0052-725 0.3-2.5 keV	00:52:08.9	-72:38:03	0.61	82.46	3074	19±3	2946	04/Jul/02
1	XTE J0052-725 2.5-10 KeV					2168	42±3		
2	SMC X-3	00:52:05.7	-72:26:04	0.62	7.78	2103	27±3	2947	20/07/02
3	CXOU J005455.6-724510	00:54:55.8	-72:45:11	0.82	503.5	518	63±12	2946	04/Jul/02
4	CXOU J005527.9-721058	00:55:27.7	-72:10:59	0.99	34.08	293	57±23	2948	04/Jul/02
5	CXOU J005323.8-722715	00:53:24.0	-72:27:16	1.00	138.04	166	59±25	2947	20/Jul/02
6	CXOU J005736.2-721934	00:57:35.9	-72:19:35	0.71	562	118	73±50	2948	04/Jul/02
7	RX J0050.8-7316	00:50:44.6	-73:16:05	0.64	319.7	417	41±20	2945	02/Oct/02

Table 1. X-ray Binary sources detected in Chandra observations 2946, 2947 and 2948.

determined to be within 15 arcmins of the known position of SMC X-3. An examination of the RXTE data shows that an outburst was detected in an observation which took place on MJD 52478, three days after the Chandra observation on MJD 52475. It is concluded that all these observations are of the same object, namely SMC X-3.

Analysis of the spectrum implies a luminosity of 27.6×10^{35} ergs s^{-1} at 60 kpc. The photon index of 0.7 indicates a relatively hard spectrum.

3.3 CXOU J005455.6-724510

An X-ray source in Observation ID 2946, which took place on 4 July 2002 (MJD 52459) between 06:48:04 and 09:47:57 was found to have a period of $503.5 \pm 6.7s$ at a $> 99\%$ level of confidence. Selective analysis of the source region was carried out to ensure that the period was not a harmonic of the 1000s Y dithering frequency. The source was subsequently independently identified using XMM data by Haberl et al. (2004) who computed the pulse period at $499.2 \pm 0.7s$. This object is very close to RX J0054.9-7245 = AX J0054.8-7244 which is listed by both Haberl & Pietsch (Haberl & Pietsch 2004) and Yokogawa et al. (Yokogawa et al., 2003) as a HMXB pulsar candidate.

3.4 CXOU J005527.9-721058

Observation ID 2948, took place on 4 July 2002 (MJD 52459) between 09:47:57 and 12:45:44. Timing analysis on this object revealed a period of $34.08 \pm 0.03s$ with a confidence of 98.5%. The position of this pulsar is within 3 arcsec of the ROSAT source 2RXP J005527.1-721100 (Rosat, 2000). The latter is co-incident with a 16.8 V magnitude optical source having a B-V colour index of -0.116 (Zaritsky et al.2002) which would be consistent with the value expected from the optical companion in a BeX-ray binary pair. To obtain the spectrum the data were first binned to 2 counts per bin.

3.5 CXOU J005323.8-722715

Observation ID 2947, took place on 20 July 2002 (MJD 52475) between 23:03:50 and 01:46:41. Timing analysis on this object revealed a period of $138.04 \pm 0.61s$ with a confidence of 98%. The position of this pulsar is coincident with emission-line star [MA93] 667 (Meyssonnier & Azzopardi, 1993)and also with MACHO object 207.16202.50. The latter shows evidence of a period of 125 ± 1.5 days. This period would be consistent with that predicted from the Corbet diagram (Corbet 1986) for a 138s Be/X-ray pulsar.

The spectrum was obtained from data binned to 2 counts per bin. It is evident that the absorbed powerlaw model gives a bad fit to the spectrum which may account for the apparent absence of N_H (less than $0.01 \times 10^{22} cm^{-2}$). A broken powerlaw model was also tried and this gave a better visual fit to the data points however the N_H value disappeared to effectively nothing which is clearly not consistent with a source located in the the SMC.

3.6 CXOU J005736.2-721934

CXOU J005736.2-721934 was originally discovered in Chandra observation 1881 on 15 May 2001 (Macomb et al. 2003) where it was reported to have a pulse period of 565.83s. It was weakly visible in observation 2948 where it was found to have a pulse period of $562 \pm 8.4s$ with a confidence of 90%.

The spectrum was obtained from data binned to 2 counts per bin.

3.7 RX J0050.8-7316

RX J0050.8-7316 has a well established pulse period of 323s (Coe et al, 2002). This period was also weakly detectable in observation 2945 although at a lower power than several other peaks and would not have been regarded as significant if the source were not already known.

4 DISCUSSION

The discovery of these pulsars brings the total number of X-ray binaries so far discovered in the SMC to 46. Figure 5 shown the number of known pulsars by date and illustrates how the steep upward trend shows no sign of levelling off. The research of Nazé et al.(2003) points to the possibility that there may be hundreds more whereas a relative comparison based on the distribution of these systems in the Milky

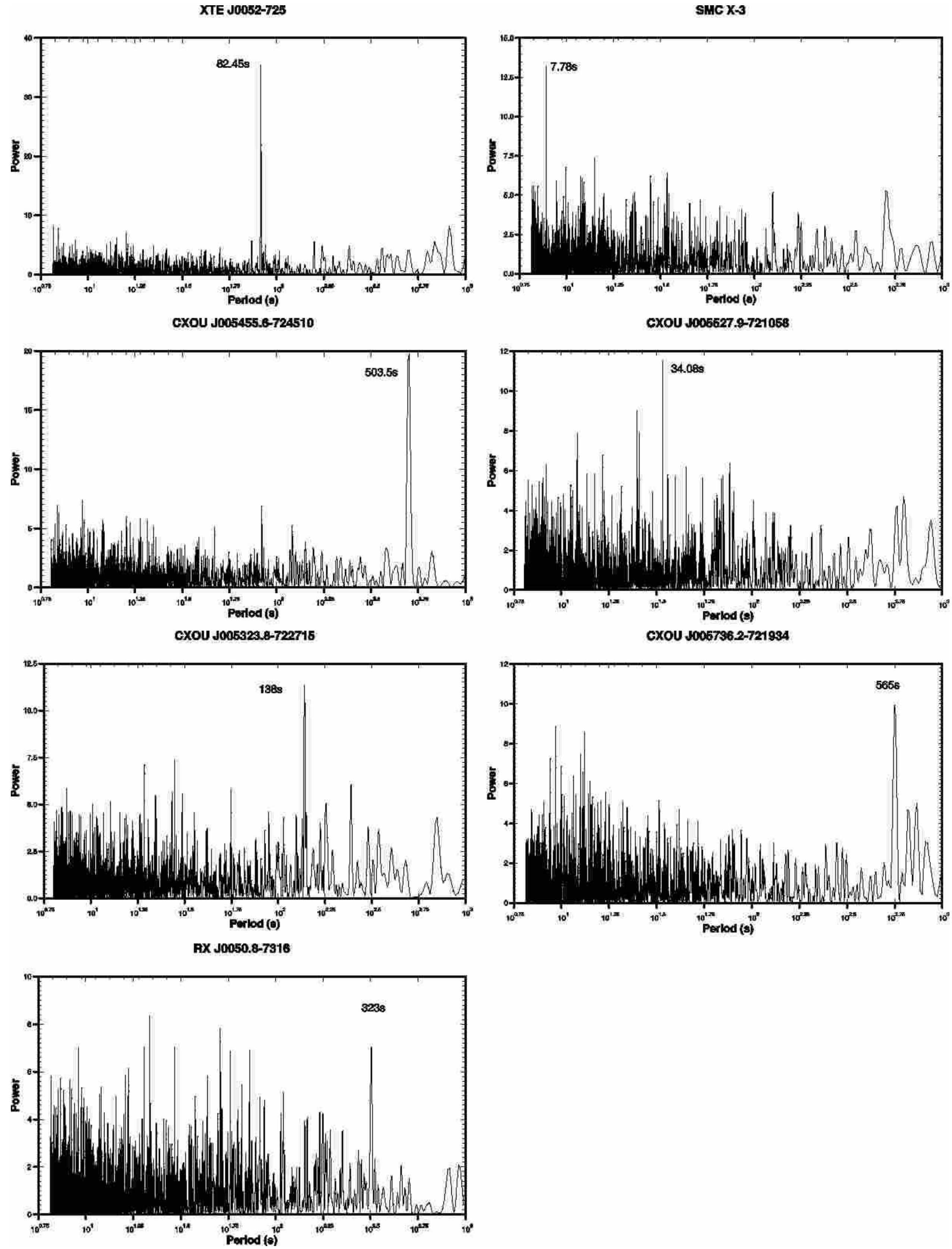

Figure 2. Power curves of all seven sources showing main periods detected using the Lomb-Scargle algorithm in Starlink PERIOD.

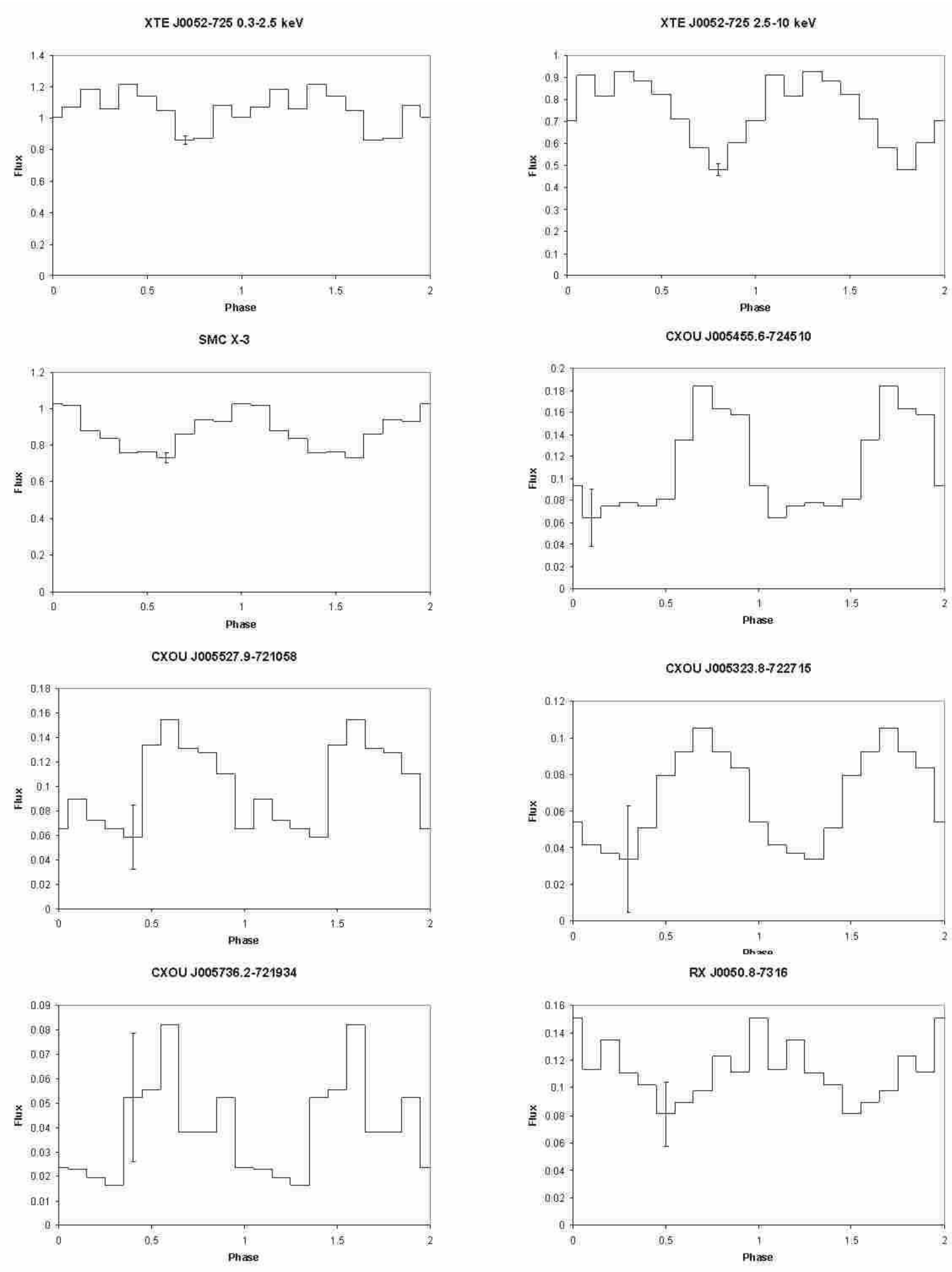

Figure 3. Pulse profiles of all seven sources with representative error bars.The top two figures show the low and high energy curves of XTE J0052-725 separately.

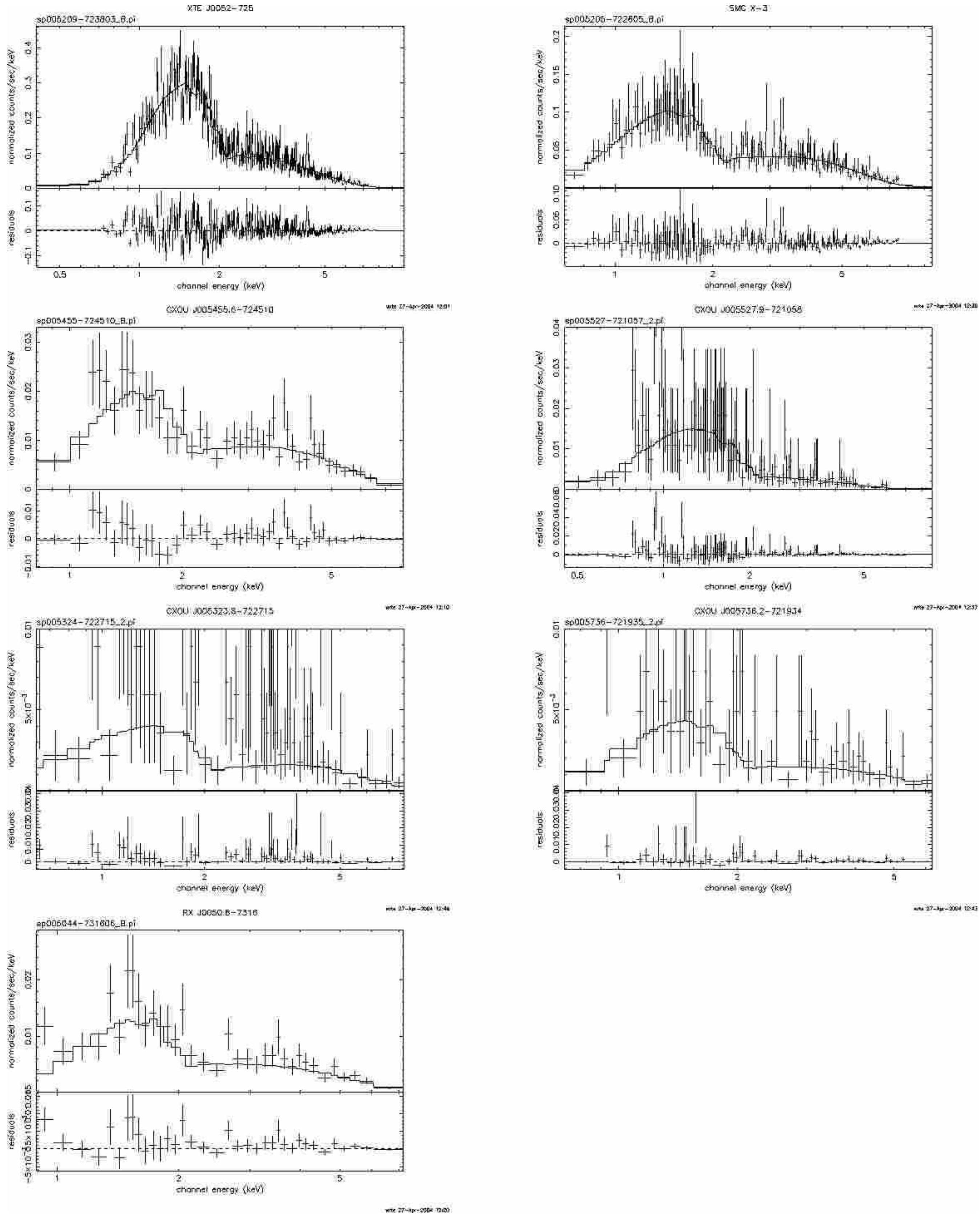

Figure 4. X-ray spectra of all seven sources. CXOU J005527.9-721058, CXOU J005323.8-722715 and CXOU J005736.2-721934 have been binned to 2 counts per bin, the remainder to 10 counts per bin.

Obj.	Name	L(Abs)X $10^{35} ergs/sec$	χ^2_v	N_{dof}	N_H $10^{22} cm^{-2}$	error	PhoIndex (Γ)	error
1	XTE J0052-725	34.19	1.11	269	0.69	0.03	1.60	0.05
2	SMC X-3	27.58	0.85	159	0.32	0.05	0.70	0.07
3	CXOU J005455.6-724510	5.54	0.80	43	0.56	0.15	0.84	0.16
4	CXOU J005527.9-721058	1.10			0.30	0.09	1.81	0.22
5	CXOU J005323.8-722715	1.18			0.00	0.37	0.43	0.29
6	CXOU J005736.2-721934	0.70			0.47	0.27	1.14	0.39
7	RX J0050.8-7316	2.78	0.95	33	0.69	0.20	1.16	0.21

Table 2. Spectral information obtained using XSPEC with an absorbed powerlaw model. A distance of 60 kpc has been assumed for all objects.

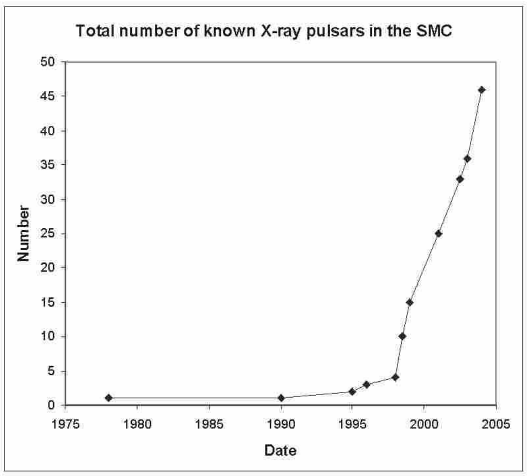

Figure 5. Number of X-ray binary pulsars known in the SMC.

Way would lead one to expect a population of perhaps one or two. Such a high density must provide clues about the star formation rates in the SMC and evidence from which a more accurate picture of its formation and recent history can be developed.

The broad range of local N_H values seen in this relatively small sample may simply reflect differing local environments or alternatively may indicate a measure of the depth of the source in the SMC. The latter may be an important effect since the work of Laney & Stobie (1986) has shown that the SMC may have a depth of 20 kpc. Further research in this area should help to formulate a more accurate three dimensional picture of the SMC.

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